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6. AUTHOR(S)

Yu-Chi Ho

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13. ABSTRACT *(Maximum 200 words)*

This grant F49620-98-1-0387 is a natural continuation of our previous grant F49620-95-1-0131 which ended on 12/31/97. Our motivation for the work reported here is the need for effective design, analysis, and optimization techniques for large, complex, stochastic Discrete Event Dynamic Systems (DEDS). DEDS are typified by communication networks, manufacturing, computer, C4I traffic and other systems governed by human-made rules and clearly important in all aspects of modern technology. In addition, we have initiated a study of hybrid systems (i.e., systems combining time-driven with even V driven dynamics) with the goat of developing a comprehensive new theory for the optimal control of such systems with direct applications to manufacturing processes. The three major research thrusts of this effort are: (1) New ways to simulate DEDS in concurrent or parallel fashion that will speed up our ability to design and analyze their performance and that are naturally matched to emerging parallel computing capabilities and software paradigms such as object-oriented programming. (2) New approaches to optimization specifically aimed at the problem of large search spaces that lack analytical structure. (3) An emerging theory for the optimal control of DEDS, as well as Hybrid Systems (HS).

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FINAL REPORT

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1. OBJECTIVES

This grant F49620-98-1-0387 is a natural continuation of our previous grant F49620-95-1-0131 which ended on 12/31/97. Our motivation for the work reported here is the need for effective design, analysis, and optimization techniques for large, complex, stochastic Discrete Event Dynamic Systems (DEDS). DEDS are typified by communication networks, manufacturing, computer, C^4I, traffic and other systems governed by human-made rules and clearly important in all aspects of modern technology. In addition, we have initiated a study of *hybrid systems* (i.e., systems combining *time-driven* with *event-driven* dynamics) with the goal of developing a comprehensive new theory for the optimal control of such systems with direct applications to manufacturing processes.

The three major research thrusts of this effort are:

• New ways to simulate DEDS in concurrent or parallel fashion that will speed up our ability to design and analyze their performance and that are naturally matched to emerging parallel computing capabilities and software paradigms such as object-oriented programming.

• New approaches to optimization specifically aimed at the problem of large search spaces that lack analytical structure.

• An emerging theory for the optimal control of DEDS, as well as Hybrid Systems (HS).

Concrete research objectives we have pursued are:

1. Investigate basic issues related to these three thrusts in terms of feasibility and intrinsic limitations.

2. Develop new methods for solving complex discrete resource allocation problems and explore extensions to more general discrete stochastic optimization settings.

3. Develop explicit algorithms that combine concurrent/parallel sample path construction techniques with Ordinal Optimization (OO) ideas and study their properties.

4. Explore a novel framework for modeling HS and develop an optimal control theory within this framework.

5. Apply the techniques we developed to some DEDS and HS problems of practical interest.

2. ACCOMPLISHMENTS/NEW FINDINGS

1. In the area of Optimization and Learning our accomplishments are summarized below:

   ▪ We have completely solved the well-known Witsenhausen problem (the determination of the optimal $f(x)$, a one-dimensional function) and our results have been accepted for publication. Completion of this work also initiated our investigation of "Granular Optimization" - an approach to search and learning in unstructured space of admissible strategies. This approach so far enables us

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to systematically search and learn in the space of one-variable functions. This result was reported in the 2000 *IEEE Conf. On Decision and Control* (CDC).

- Our research on Bayesian Learning methodologies in computational intelligence has led us to study the feature selection problem in automatic target recognition. This is a combinatorial optimization problem Preliminary results of working with real M-Star data have been encouraging.

- We have gained further insight into the No-Free-Lunch theorem and its implications. This further reinforces the importance of learning.

- Since computational resources for optimization and learning are always limited in practice, we have initiated the study of the auxiliary problem of optimizing the allocation of computing resources in search and learning. This approach is just beginning and reported more fully in our renewal proposal to this contract.

- *Relationship to original goals*: This work is within the scope of Objectives 1,3, and 5 (see section 1).

- *Relevance to AF mission and potential applications:* The work directly and indirectly will be helpful in a variety of AF guidance and control mission work, where search and adaptation are necessary.

2. In the area of discrete stochastic optimization problems, we were able to show that it is possible to transform a *discrete* stochastic optimization problem into a companion *continuous* optimization problem, which is generally easier to solve and the solution of which is readily transformed into the solution of the original problem. We were also able to extend this approach beyond the original resource allocation setting we were studying and tackled the well-known "lot sizing" problem in manufacturing for solution using this "surrogate problem" methodology. We have been able to demonstrate the effectiveness of this approach for multiclass single-stage manufacturing systems and have published our findings.

- *Relationship to original goals*: This work is being pursued in the context of Objectives 2,3 (see section 1).

- *Relevance to AF mission and potential applications*: Discrete stochastic optimization problems are common in practice, as mentioned above. A major obstacle in dealing with these problems is the computational complexity which slows down the process of decision making. This approach holds great promise for significantly faster decisions making capabilities, at least for certain types of problems.

3. While researching discrete stochastic optimization problems, we encountered a well-known scheduling problem in air traffic control referred to as "ground holding control". The problem is to schedule aircraft so as to minimize airborne delays due to congested destination airports and weather-related difficulties. We found out that applying principles from sample path analysis of DEDS leads to optimization schemes much more efficient than other approaches in the literature and guaranteeing global optimality. This work has resulted in a journal publication scheduled to appear

ip to original goals: This work falls under Objectives 3,5 (see section 1).

AF mission and potential applications: Air traffic control is of obvious the Air Force. In addition, the methodology we used holds promise for ems thus far tackled only through linear or dynamic programming techniques that are generally always suited to real-time decision making.

4. We have established a novel modeling framework for Hybrid Systems (HS), i.e., systems combining *time-driven* with *event-driven* dynamics. Based on this framework, we have been able to solve a class of optimal control problems motivated by concrete single-stage manufacturing problems. We were able to show that a decomposition of the optimal state trajectory in such problems allows us to reduce the complexity of solution algorithms from exponential to linear. Explicit numerical results can be seen through interactive java applets found in *http://vita.bu.edu/cgc/Hybrid*. We have also made progress in studying problems for multi-stage hybrid systems based on an approximation method reported in some of our published work. Explicit numerical results can also be obtained through an interactive java applet at *http://vita.bu.edu/cgc/newhybrid/*.

* *Relationship to original goals*: This work is being pursued in the context of Objectives 4,5 (see section 1).

* *Relevance to AF mission and potential applications*: New technological systems increasingly exhibit hybrid dynamic characteristics as computers are continuously integrated with traditional time-driven processes. The IBR problem of great interest to the AF and part of an ongoing manufacturing process at the Wright-Patterson Air Force Base is an example of such a system.

3. PUBLICATIONS

• Papers Published:

[1]   Panayiotou, C.G., and Cassandras, C.G., "A Sample Path Approach for Solving the Ground Holding Policy Problem in Air Traffic Control", to appear in *IEEE Trans. on Control Systems Tech.*, 2001.

[2]   Cho, Y.C., Cassandras, C.G., and Pepyne D.L., "Forward Decomposition Algorithms for Optimal Control of a Class of Hybrid Systems", to appear in *Intl. J. of Robust and Nonlinear Control*, 2001.

[3]   J.T. Lee , E.T.W.Lau, and Y.C.Ho ,"The Witsenhausen Counterexample: A Hierarchical Search Approach for Non-Convex Optimization Problems," to appear in *IEEE Transactions on Automatic Control*, 2001.

[4]   Wardi, Y., Cassandras, C.G., and Pepyne D.L., "A Backward Algorithm for Computing Optimal Controls for Single-Stage Hybrid Manufacturing Systems", to appear in *Intl. J. of Production Research*, 2001.

[5]   Cassandras, C.G., Pepyne D.L., and Wardi, Y., "Optimal Control of a Class of Hybrid Systems", to appear in *IEEE Trans. on Automatic Control*, 2001.

[6]   Gokbayrak, K., and Cassandras, C.G., "An On-Line 'Surrogate Problem' Methodology for Discrete Stochastic Resource Allocation Problems", *J. of Optimization Theory and Applic.*, Vol. 108, 2, pp. 349-376, 2001.

[7]   Cho, Y.C., Cassandras, C.G., and Pepyne D.L., "Forward Algorithms for Optimal Control of a Class of Hybrid System ", *Proc. of 39h IEEE Conf. Decision and Control*, pp. 975-980, December 2000.

[8]   Cho, Y.C., and Cassandras, C.G., "Optimal Control of Steel Annealing Processes as Hybrid Systems", *Proc. of 39h IEEE Conf. Decision and Control*, pp. 540-545, December 2000.

[9]   Gokbayrak, K., and Cassandras, C.G., "A Hierarchical Decomposition Method for Optimal Control of Hybrid Systems", *Proc. of 39h IEEE Conf. Decision and Control*, pp. 1816-1821, December 2000.

[10]   Panayiotou, C.G., and Cassandras, C.G., "Call Allocation in Cellular Communication Systems with Overlapping Coverage", *Proc. of 39h IEEE Conf. Decision and Control*, pp. 55-60, December 2000.

[11]   Panayiotou, C.G., Cassandras, C.G., and Gong, W.B., "Model Abstraction for Discrete Event Systems Using Neural Networks and Sensitivity Information", *Proc. of 2000 Winter Simulation Conf.*, December 2000.

[12]   D. Li , L. Lee, and Y.C. Ho, "Vector Ordinal Optimization - A New Heuristic Approach and its Application to Computer Network Routing Design Problems," *International Journal of Operations and Quantitative Management*, 5, #5, pp. 211-230, 1999.

[13]   X.H. Guan, E. Ni, Y.C. Ho, and P. Luh, "Optimization Based Bidding Strategies and Gaming Analysis for Deregulated Electric Power Markets," to appear as Chapter in *Electric Power Systems*, Kluwer Academic Publisher, 2001.

[14]   Ho, Y.C., Cassandras, C.G., Chen, C-H., and Dai, L., "Ordinal Optimization and Simulation", *J. of Operational Research Society*, Vol. 51, 4, pp. 490-500, 2000.

[15]   L.H. Lee, F.H. Abernathy, and Y.C. Ho, "Production Scheduling for Apparel Manufacturing Systems", *Production Planning and Control*, 11, #3, 2000, 281-290.

[16]   Y.C. Ho, "At the Gates of the Millennium: Are We in Control?", Panel discussion report, *IEEE Control Systems Magazine*, Vol. 20, #1, Feb. 2000.

[17]   Dai, L., Cassandras, C.G., and Panayiotou, C.G., "On the Convergence Rate of Ordinal Optimization for a Class of Stochastic Discrete Resource Allocation Problems", *IEEE Trans. on Automatic Control*, AC-45, 3, pp. 588-591, 2000.

[18]   Pepyne D.L., and Cassandras, C.G., "Optimal Control of Hybrid Systems in
         Manufacturing", *Proceedings of the IEEE*, Vol. 88, 7, 2000.

[19]   Gokbayrak, K., and Cassandras, C.G., "Hybrid Controllers for Hierarchically
         Decomposed Systems", *Proc. of 2000 Hybrid System Control Conf.*, pp. 117-
         129, March 2000.

[20]   Cassandras, C.G., Panayiotou, C.G., Diehl, G., Gong, W.B., Liu, Z., and Zou, C.,
         "Clustering Methods for Multi-Resolution Simulation Modeling", *Proc. of
         SPIE 14h Annual Intl. Symposium*, April 2000.

[21]   Cassandras, C.G., and Yu, R., "A 'Surrogate Problem' Approach for Lot Size
         Optimization in Manufacturing Systems", *Proc. of 2000 American Control
         Conf.*, pp. 3279-3283, June 2000.

[22]   Gokbayrak, K., and Cassandras, C.G., "Constrained Optimal Control for
         Multistage Hybrid Manufacturing System Models", *Proc. of 8th IEEE Medit.
         Conference on New Directions in Control and Automation*, July 2000.

[23]   Cassandras, C.G., and Lafortune, S., *Introduction to Discrete Event Systems*,
         Kluwer Academic Publ. (822 pages), 1999.

[24]   Y.C. Ho, "Optimization - a Many Splendored Thing", 90-minute IFAC World
         Congress Plenary speech on CD-ROM (with animated powerpoint slides and ·
         synchronized voice), self-published.

[25]   Panayiotou, C.G., and Cassandras, C.G., "Optimization of Kanban-Based
         Manufacturing Systems", *Automatica*, Vol. 35, pp. 1521-1533, 1999.

[26]   Gokbayrak, K., and Cassandras, C.G., "Stochastic Discrete Optimization Using a
         Surrogate Problem Methodology", *Proc. of 38h IEEE Conf. Decision and
         Control*, pp. 919-924, December 1999.

[27]   Cassandras, C.G., Liu, Q., Pepyne, D., and Gokbayrak, K., "Optimal Control of a
         Two-Stage Hybrid Manufacturing System Model", *Proc. of 38h IEEE Conf.
         Decision and Control*, pp. 450-455, December 1999.

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         Manufacturing System Model", *Proc. of 38h IEEE Conf. Decision and
         Control*, pp. 919-924, December 1999.

[29]   Panayiotou, C.G., and Cassandras, C.G., "A Sample Path Approach for Solving
         the Ground Holding Policy Problem in Air Traffic Control", *Proc. of 38h
         IEEE Conf. Decision and Control*, pp. 2450-2455, December 1999.

[30]   Y.C. Ho, "A Tutorial on Ordinal Optimization", 113, pp. 169-192, Jan. 1999.

[31]   Y.C. Ho, "The No Free Lunch theorem and the Human Machine Interface", *IEEE
         Control Systems Magazine*, June 1999.

[32]   E.T.W. Lau and Y.C. Ho, "Super-Heuristics and Their Applications to Combinatorial
         Problems", *Asian Journal on Control*, Vol.1, #1, May 1999.

[33] M. Deng, and Y.C. Ho "Sampling Selection Method for Ordinal Optimization", *AUTOMATICA*, 35, #2, 1999.

[34] Pepyne D.L., and Cassandras, "Performance Optimization of a Class of Discrete Event Dynamic Systems Using Calculus of Variations Techniques", *J. of Optimization Theory and Applic.*, Vol. 100, 3, pp. 599-622, 1999.

[35] Cassandras, C.G., and Lafortune, S., "Discrete Event Systems: The State of the Art and New Directions", *Applied and Comput. Control, Signals, and Circuits*, Vol. 1, pp.1-65, 1999.

[36] Cassandras, C.G., and Panayiotou, C.G., "Concurrent Sample Path Analysis of Discrete Event Systems", *J. of Discrete Event Dynamic Systems,* Vol. 9, 2, pp. 171-195, 1999.

[37] Cassandras, C.G., and Pepyne D.L., "Hybrid System Models for Integrated Manufacturing", *Proc. of IEEE Hong Kong Symposium on Robotics and Control* , Vol. II, pp. 615-620, July 1999.

[38] Panayiotou, C., and Cassandras, C.G., "Optimization of Kanban-Based Manufacturing Systems", *Proc. of 14th IFAC World Congress*, Vol. J, pp. 139-144, July 1999.

[39] L.H. Lee, E.T.W. Lau, and Y.C. Ho, "Explanation Of Goal Softening in Ordinal Optimization", *IEEE Trans. on Automatic Control*, 43, #9, 1998.

[40] Pepyne, D.L., and Cassandras, C.G., "Design and Implementation of an Adaptive Dispatching Controller for Elevator Systems During Uppeak Traffic", *IEEE Trans. on Control Systems Tech.*, Vol. 6, 5, pp. 635-650, 1998.

[41] Panayiotou, C.G., and Cassandras, C.G., "Flow Control for a Class of Transportation Systems", *Proc. of 1998 IEEE Conf. on Control Applications*, September 1998.

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[43] Cassandras, C.G., Pepyne D.L., and Wardi, Y., "Generalized Gradient Algorithms for Hybrid System Models of Manufacturing Systems", *Proc. of 37th IEEE Conf. Decision and Control*, pp. 2627-2632, December 1998.

[44] Cassandras, C.G., Pepyne D.L., and Wardi, Y., "Optimal Control of Systems with Time-Driven and Event-Driven Dynamics", *Proc. of 37th IEEE Conf. Decision and Control*, pp. 7-12, December 1998.

[45] M.S. Yang, L.H. Lee, and Y.C.Ho, "Inference Based Ordinal Optimization and Its Applications", *Proc. of 1998 Workshop on Discrete Event Systems*, pp. 367-372, August 1998.

[46] Y.C.Ho, "Review of the Book: Neuro-Fuzzy and Soft Computing" by Jang-Sun-Mizutani, *IEEE Trans. on Automatic Control*, 42, #9, 1997, 727-729.

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[49] Pepyne D.L., and Cassandras, "Modeling, Analysis, and Optimal Control of a Class of Hybrid Systems", *J. of Discrete Event Dynamic Systems*, Vol. 8, 2, pp. 175-201, 1998.

[50] Panayiotou, C., and Cassandras, C.G., "Dynamic Transmission Scheduling for Packet Radio Networks", *Proc. of 1998 IEEE Symposium on Computers and Communication*, July 1998.

[51] Cassandras, C.G., Pepyne D.L., and Wardi, Y., "Optimal Control of Hybrid Systems and Some Manufacturing Process Applications", *Proc. of 1998 Intl. Workshop on Discrete Event Systems*, pp. 361-366, August 1998.

[52] Pepyne, D.L., and Cassandras, C.G., "Optimal Dispatching Control for Elevator Systems During Uppeak Traffic", *IEEE Trans. on Control Systems Tech.*, Vol. 5, 6, pp. 629-643, 1997.

[53] Cassandras, C.G., Dai, L., and Panayiotou, C.G., "Ordinal Optimization for a Class of Combinatorially Hard Problems", *Proc. of 1997 Intl. Conf. on Intelligent Systems and Semiotics*, pp. 173-174, September 1997.

[54] Pepyne D.L., and Cassandras, C.G., "A Calculus of Variations Approach to the Optimal Control of Discrete Event Dynamic Systems", *Proc. of 36th IEEE Conf. Decision and Control*, pp. 3550-3555, December 1997.

[55] Cassandras, C.G., Dai, L., and Panayiotou, C.G., "Ordinal Optimization for Deterministic and Stochastic Resource Allocation", *Proc. of 36th IEEE Conf. Decision and Control*, pp. 662-667, December 1997.

[56] Cassandras, C.G., and Pepyne D.L., "Optimal Control of a Class of Hybrid Systems", *Proc. of 36th IEEE Conf. Decision and Control*, pp. 133-138, December 1997.

[57] Pepyne, D.L., and Cassandras, C.G., "Adaptive Dispatching Control for Elevator Systems During Uppeak Traffic", *Proc. of 36th IEEE Conf. Decision and Control*, pp. 133-138, December 1997.

• Submitted, but not yet accepted:

[1]   Guan, X., Ho, Y.C., and Lai, F., "An Ordinal Optimization Based Bidding
        Strategy for Electric Power Suppliers in the Daily Energy Market", subm.
        for publication, 2000.

[2]   C. Martin and Y.C. Ho, "Value of information in the Polya Urn Problem", submitted to
        Information Sciences 2000

[3]   M. Ozden and Y.C.Ho, "A Probabilistic Solution Generator of Good Enough Designs for
        Simulation" submitted to *European Journal of Operations Research*, 2000

[4]   Panayiotou, C.G., and Cassandras, C.G., "Call Allocation in Cellular
        Communication Systems with Overlapping Coverage", subm. to *IEEE Trans.
        On Communications*, 2000.

4. PERSONNEL SUPPORTED

• Principal Investigators:

>   Yu-Chi Ho, Professor, Harvard University
>
>   Christos G. Cassandras, Professor, Boston University

• PostDoc:

>   Edward T.W.Lau, David Pepyne, Harvard University

• Graduate Students:

>   Mike Yang, J.T.Lee, X.C. Lin, Z.H. Chen, Harvard University
>
>   Kagan Gokbayrak, Rui Yu, Qinjia Liu, Boston University

5. INTERACTIONS/TRANSITIONS

Participation/Presentations at Meetings, Conferences, Seminars

Y.C. Ho gave invited talks/courses at the following meetings/organizations:
• Plenary address at the *1997 Intl. Conf. on Intelligent Systems and Semiotics* (9/24/97)
• Short course on DEDS at the *36th IEEE Conf. Decision and Control*, (12/10/97)
• Plenary Lecture at the *36th IEEE Conf. Decision and Control* (12/11/97)
• NSF sponsored Japan-US-Vietnam Workshop (5/13/98)
• Plenary address at the *1998 Intl. Workshop on Discrete Event Systems* (WODES98)
  (8/27/98)

Rome Workshop on DES (8/31/98)

Foundation Workshop on Control Education, University of Illinois,

at IFAC World Congress, July 5,1999

on DEDS at the *IFAC World Congress* (7/4/99)

- Nanyang Technological University, Singapore (5/18/99)
- Xian Jiaotong University (6/28-30/99)

12/8/99	CDC '99 workshop on complexity
12/9/99	CDC'99 panel on 21st Century Control
1/13/00	ONR Monterey Workshop
1/26/00	Boston Chapter of Control Systems Society
4/21/00	NSF Mini-Workshop on Electric Power
5/18/00	US Army Corp of Engineers
6/7/00	EPRI/DoD workshop on Complex Systems

C.G. Cassandras gave invited talks/courses at the following meetings/organizations:

- *1997 Intl. Conf. on Intelligent Systems and Semiotics*, Gaithersburg, MD, September 1997
- University of Wisconsin, Madison, WI, November 1997
- *36th IEEE Conference on Decision and Control*, San Diego, CA, December 1997
- Short course on DEDS at the *36th IEEE Conf. Decision and Control*, December 1998
- *12th SPIE Intl. Symposium/Simulation Conference*, Orlando, FL, April 1998
- WPAFB AFOSR Workshop, Dayton, OH, July 1998
- *1998 Intl. Workshop on Discrete Event Systems* (WODES98), Cagliari, Italy, August 1998
- University of Rome Workshop on DES, Rome, Italy, August 1998
- *National Science Foundation Workshop on Control Education*, University of Illinois, October 1998
- *1998 IEEE Conf. on Control Applications*, Trieste, Italy, September 1998
- University of Pennsylvania, Philadelphia, PA, November 1998
- *37th IEEE Conference on Decision and Control*, Tampa, GLA, December 1998 (3 inv. talks)
- *NOKIA Research*, Burlington, MA, April 1999
- *13th SPIE Intl. Symposium/Simulation Conference*, Orlando, FL, April 1999
- Case Western Reserve University, Cleveland, OH, April 1999
- *IEEE Hong Kong Symposium on Robotics and Control*, Hong Kong, July 1999

- Hong Kong University of Science and Technology, Hong Kong, July 1999
- Short course on DEDS at the *IFAC World Congress* (7/4/99)

- *INFORMS Conf.,* Philadelphia, PA, November 1999 (invited talk)
- *38th IEEE Conference on Decision and Control*, Phoenix, AZ, December 1999 (3 invited talks)
- Tutorial Workshop on Stochastic Complex Systems at *38th IEEE Conference on Decision and Control*, Phoenix, AZ, December 1999
- *Boston Chapter of IEEE Control Systems Society*, Panel on *Control Challenges for the New Century*, Cambridge, MA, January 2000
- *14th SPIE Intl. Symposium/Simulation Conference*, Orlando, FL, April 2000 (invited talk)
- *Hanscom Air Force Base*, Concord, MA, June 2000
- *2000 American Control Conf.*, Chicago, IL, June 2000 (invited talk)
- *National Science Foundation Workshop on Logic Control for Manufacturing Systems*, Ann Arbor, MI, June 2000 (invited speaker)
- *National Science Foundation National Workshop for High School Teachers of Math and Science,* Chicago, IL, June 2000 (invited speaker)
- *Intl. Workshop on Formal Methods for Performance Analysis*, Nijmegen, The Netherlands, July 2000 (invited speaker)
- Plenary Address at *8th IEEE Medit. Conference on New Directions in Control and Automation*, Patras, Greece, July 2000
- Technion Inst. of Technology, Haifa, Israel, July 2000 (invited seminar)
- Mini-Course on Hybrid Systems, *5th Intl. Workshop on Discrete Event Systems*, Ghent, Belgium, August 200
- Northeastern University, Boston, MA, October 2000

Consultative and Advisory Functions

Y.C. Ho: National Research Council Panel on Modeling and Simulation

C.G. Cassandras:
- Alphatech, Inc., Contact person: David Logan
- Wright-Patterson Air Force Base. Contact person: Dr. Jim Malas, WPAFB.
- ALCOA, Contact persons: Ken Schrock, Jeanette Nymon

Transitions

• *Dynamic control of transportation system for mining output, RTZ-CRA Co.*

RTZ-CRA of Melbourne, Australia, contacted C.G. Cassandras for assistance in adopting Perturbation Analysis and other DEDS-related techniques for improving transportation operations in a major mining activity. Several ideas (including the concurrent simulation ideas developed in this project) were developed and considered for technology transfer at RTZ-CRA. Contact person: Dr. Russell Garnsworthy.

• *Modeling and system integration of large-scale manufacturing systems, ALCOA*

ALCOA has worked with C.G. Cassandras on DEDS-related techniques for effective modeling and control of large manufacturing facilities (thousands of products, hundreds of workcenters) where even elementary data collection and entry into software tools are infeasible. In addition, it is necessary to integrate physical processes with operations management, a perfect example of a hybrid system which has motivated some of the new research ideas for grant F49620-98-1-0387. Several proposed new concepts are being considered by ALCOA. Contact persons: Ken Schrock, Jeanette Nymon.

• *Stochastic optimization methods applied to JFACC dynamic mission planning, Alphatech*

C.G. Cassandras is currently working with Alphatech, Inc. on DEDS-related techniques for effective modeling and control of military operations in the JFACC setting. Several of the stochastic optimization techniques developed under this AFOSR project are being tested at Alphatech for the purpose of effective dynamic mission planning to overcome computational complexity issues. Contact person: David Logan.

6. NEW DISCOVERIES, INVENTIONS, OR PATENT DISCLOSURES

None over the reporting period.

7. HONORS/AWARDS

Y.C.Ho (Lifetime):
Guggenheim Fellow (1970), Fellow of IEEE (1972), Distinguished Member of IEEE Control System Society (1985), Member of National Academy of Engineering (1987), IEEE Control Science and Engineering Field Award (1989), Chiang Technology Achievement Prize (1993).

C.G. Cassandras (Lifetime):
Lilly Fellow (1991), Fellow of IEEE (1996), IFAC Harold Chestnut Prize (1999)

Honors/Awards received during grant period:

Y.C. Ho:
AACC Bellman Heritage Award (1999)
ASME Oldenburger Award for Control Systems (1999).
Elected as a foreign member of the Chinese Academy of Sciences AND the Chinese

Academy of Engineering (2000).

C.G. Cassandras received the Harold Chestnut Prize awarded by the International Federation on Automatic Control for Best Control Engineering Textbook in July 1999. He was appointed Editor-in-Chief of the *IEEE Transactions on Automatic Control*, in July 1998.